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# A model comparison of early Holocene orbital insolation and present-day anthropogenic CO2 climate forcings and their influences on Alaskan ecosystems

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A model comparison of early Holocene orbital insolation and present-day anthropogenic $CO_2$ climate forcings and their influences on Alaskan ecosystems

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A MODEL COMPARISSON OF EARLY HOLOCENE ORBITAL INSOLATION AND PRESENT-DAY ANTHROPOGENIC CO2 EMISSIONS AND THEIR INFLUENCE ON ALASKAN ECOSYSTEMS

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**Table of Contents**

**List of Figures**

**List of Tables**

**Abstract**

Many of Alaska's ecosystems play an integral role in extracting and sequestering carbon from the Earth's atmosphere. There is great concern that future climate warming will reduce the ability of these ecosystems to maintain their status as carbon sinks. There have been other warm periods in Earth's history, and there are some lessons to be learned by comparing these periods to the current period of global warming. The Holocene Thermal Maximum (HTM) was one such recent warm period and a time when many of Alaska's peatlands experienced rapid vertical accumulation.

Using the National Center for Atmospheric Research's (NCAR) Community Earth System Model (CESM) in conjunction with a Terrestrial Ecosystem Model (TEM-Hydro), I compared the effects of current anthropogenic climate change to the HTM on ecosystem functions. Results indicate that regions of permafrost in Alaska are currently more expansive along Alaska's North Slope than at 10 ka. Drier lowlands at present are less conducive to the accumulation of organic carbon compared to 10 ka. Boreal forests are more productive at present due to increased $CO_2$ fertilization resulting in a larger carbon sink than at 10 ka. Future increases in atmospheric $CO_2$ concentrations beyond those of today threaten to thaw more permafrost and dry more wetland area than in these experiments, yielding potentially larger carbon sources, and exacerbating anthropogenic $CO_2$ emissions.

## I. Introduction

The Earth's climate is currently experiencing a period of rapid change and significant warming from increased atmospheric $CO_2$ concentrations (Keeling et al., 1979; IPCC, 2007). Impacts of anthropogenic greenhouse warming are more pronounced at higher latitudes than lower latitudes (i.e. the Arctic and Antarctic; Ramanathan et al., 1979; Ramanathan, 1988; IPCC, 2007). Deep-well temperatures in permafrost confirm that the Artic is more susceptible to the impacts of climate change. One analysis of temperature profiles in permafrost indicate a 2 °C – 4 °C warming over the past century along Alaska's North Slope (Lachenbruch and Marshall, 1986). This analysis is corroborated by instrumental data that indicates temperatures in Alaska have risen approximately 4 °C over the past century (Backlund et al., 2008). Additionally, the observed warming has resulted in unprecedented melting of multiyear sea ice (sea ice that has survived one full melt season) in the Arctic (Johannessen et al., 1999; Comiso, 2002). These and other changes have the potential to trigger numerous mechanisms that could move large quantities of carbon that are currently sequestered in Alaskan ecosystems into the atmosphere (Gruber et al., 2004). Some of these mechanisms that are of particular concern for Alaskan ecosystems include: the thawing of permafrost, the drying of wetlands, and changes to land-use and fire regimes in boreal forests (Field and Raupach, 2004).

Permafrost is widespread in the Northern Hemisphere's Arctic and boreal regions. In these regions, permafrost covers approximately 22% of the landscape (Zhang et al., 1999). Permafrost can be a few hundred meters thick in northern regions where it is continuous; farther south, permafrost is typically less continuous and may only be a few meters thick (Yershov, 1998). Permafrost has a large variation in the amount of organic carbon sequestered in the frozen soils. The permafrost in some locations of Alaska may be composed of 50% organic carbon or more (Bockheim, 2006). Increases in temperature will thaw permafrost and result in a net loss of permafrost (Shuur et al., 2008). Thawing of permafrost will accelerate microbial decomposition of the newly-mobilized organic carbon that was previously stored in the now-thawed permafrost (Shuur et al., 2008).

Peatlands accumulate in regions where anaerobic conditions limit decomposition rates, and productivity is greater than the decomposition (Frolking et al., 2001; Charman, 2002; Yu et al., 2009; Jones and Yu, 2010). Significant warming from elevated atmospheric $CO_2$ concentrations will have two impacts on peatlands: 1) warming may increase the productivity of peatland vegetation, and 2) warming may increase peatland decomposition rates, limiting carbon accumulation (Yu et al., 2009). Furthermore, one recent study suggests that elevated atmospheric $CO_2$ concentrations will trigger a major redistribution of precipitation that could lead to drying of Alaska's wetlands (Backlund et al., 2008), which may release $CO_2$ via increased microbial decomposition (Shuur et al., 2008). On the other hand, melting permafrost may create additional wetlands, so the net effect of climate changes is unclear.

Boreal forests account for roughly 31% of all global soil carbon (Gower et al., 1997; calculated from Schlesinger, 1991). It has been shown that increased summer temperatures are associated with higher productivity of boreal forests during the growing season, resulting in increased carbon uptake from the atmosphere (Keeling et al., 1996; Myneni et al., 1997). Although there is a well-established relationship between temperature and productivity, temperature-induced drought stress has limited growth in some of Alaska's boreal forests over the past few decades (Barber et al., 2000). Additionally, warmer temperatures during the winter have been shown to increase plant respiration, providing more carbon to the atmosphere (Chapin et al., 1996). Another method for boreal forests to return carbon to the atmosphere is via combustion. It is estimated that 7% of global NPP is returned to the atmosphere by fires annually (Cramer et al., 1999; Andreae and Merlet, 2001; Hicke et al., 2003). Alaskan forests will likely experience increased fire disturbance in the future, releasing more $CO_2$ to the atmosphere and altering the carbon dynamics of the region (McGuire, 2006).

Although increases in temperature and atmospheric $CO_2$ are leading to changes in Alaskan ecosystems, it is difficult to separate the impacts of warming from those of elevated $CO_2$. Fortunately, the Earth has experienced warm periods in the past, and these time periods can be studied to better understand past ecosystem responses to these variables. Proxy and model-based reconstructions of the climatology and ecology of past warm periods can be compared to future warming scenarios, allowing inferences to be made about how Alaskan ecosystems may respond to a warmer climate in the future.

One of the most recent warm periods in the Earth's history was the Holocene Thermal Maximum (HTM; Bartlein et al., 1998; Crucifix et al., 2002). The HTM was the result of orbital-scale climate variations related to changes in the Earth's rotation and orbit; as a result, the Earth experienced perihelion during the boreal summer (Berger and Loutre, 1991; COHMAP, 1988). The altered timing of perihelion resulted in an increase in summer insolation of approximately 50 $W/m^2$ for the latitudes encompassing Alaska (Berger and Loutre, 1991). There was a nearly identical reduction of fall and winter insolation, resulting in a minimal increase in the Earth's energy balance of approximately 1 W/m$^2$ annually (Berger and Loutre, 1991). The HTM occurred approximately 10,000 years ago in Alaska at the height of maximum insolation seasonality, making Alaska an ideal study site to examine the impacts of warming due to orbital forcing and not elevated $CO_2$ (COHMAP, 1988; Kaufman et al., 2004).

Many parts of Alaska were at least 2 °C warmer during the HTM summer than preindustrial temperatures as a result of increased summer insolation (Anderson and Brubaker, 1993; Anderson et al., 2004; Kaufmann et al., 2004). Increases in summer temperature also had a significant impact on ecosystem structure and function during the HTM (e.g. Overpeck et al., 2005; CSAS, 2008). For example, upland vegetation in Alaska shifted from non-analog vegetation types dominated by Poplar and Willow around 11,000 years ago (Williams and Jackson, 2007), to a Spruce-dominated boreal forest in eastern Alaska approximately 9,000 years ago. Similar Spruce-dominated boreal forests established at least 3,000 years later in other regions of Alaska (Yu et al., 2009). This shift in upland vegetation is indicative of drier uplands during the HTM, which may be attributed to reduced soil moisture in forested regions during the summer months. Interestingly, Alaskan peatlands experienced a period of rapid vertical accumulation during the HTM (Yu et al., 2009; Jones and Yu, 2010). This increase suggests that lowlands in Alaska were wetter during the HTM, possibly as a result of increased spring and summer snowmelt. However, causes of the differences in the response of upland and lowland ecosystems to the HTM remain uncertain, and modeling approaches can potentially provide valuable insight.

Although the HTM and the recent anthropogenic warming both resulted in a warmer Alaskan summers, significant differences in seasonality exist between these two events. Increased insolation seasonality during the HTM led to increased temperature seasonality (i.e. warmer summer and colder winters; COHMAP, 1988). Elevated atmospheric $CO_2$ concentrations have resulted in more warming during the winter than the summer, reducing temperature seasonality when compared to preindustrial temperatures (Chapman and Walsh, 1993).

Despite the differences in temperature seasonality, there is still much that can be learned from a direct contrast of the climate and ecosystem responses to the HTM and anthropogenic warming. For example, warmer summers coupled with warmer winters in the future will likely result in a significant reduction of permafrost in Alaska when compared to the HTM. The reduced permafrost extent in the future will likely mobilize previously sequestered organic carbon providing a source of atmospheric carbon through methane emissions. Additionally, I hypothesize that Alaskan peatlands during the HTM were a much larger carbon sink than they will be in the future. Reduced spring snowmelt and a redistribution of precipitation associated with elevated atmospheric $CO_2$ concentrations will potentially result in drier wetlands than at 10 ka (1 ka =1000 cal yr BP), thus destabilizing the water table and increasing microbial decomposition. The reduction of carbon accumulation in Alaskan peatlands will provide a positive feedback to future anthropogenic $CO_2$ emissions. Finally, since Net Primary Productivity (NPP) is primarily limited by temperature, I hypothesize that boreal forests in Alaska will be more productive in the future than during the HTM due to future warming surpassing that of the HTM. However, increases in fire season length will likely result in a larger source of carbon to the atmosphere than during the HTM.

Using NCAR's Community Earth System Model (CESM), I investigate the primary differences between climate change induced by altering the Earth's orbital parameters and climate change forced by increased atmospheric $CO_2$ concentrations. I use the climatology output from my CESM experiments to force a terrestrial ecosystem model (TEM), as well as infer changes to Alaska's hydro-meteorological climate in my model experiments. Using TEM, I examine the implications of these two climate change scenarios on the carbon accumulation rates in Alaska's wetlands and productivity of Alaska's boreal forests.

## 2. Methods

*2a. CESM Model*

The Community Earth System Model (CESM) is a fully coupled climate model comprised of multiple components, including, land, atmosphere, ocean, sea ice, and land ice models. CESM contains numerous different component setups that allow the model to be applied to a range of questions and computational resources. For this study I used the “E1850CN” component set at the “f19_g16” resolution, which is characterized by fully coupled land-atmosphere models, a dynamic sea ice model, and slab ocean model in a pre-industrial environment (Vertenstein et al., 2010). The atmosphere model (CAM 4.0; Eaton, 2010) has a resolution of 1.9° x 2.5° and a total of 26 vertical levels. The land model (CLM 4.0; Oleson et al., 2010) has a resolution equivalent to CAM at 1.9° x 2.5° and includes 15 vertical levels in the soil. The ocean model has a resolution of approximately 1° x 1°. The use of the Slab Ocean Model (SOM), rather than prescribed sea-surface temperatures, allowed me to run the prognostic sea ice model (CICE 4.0; Bailey et al., 2010) at the same 1° x 1° resolution as the slab ocean model. The land ice model was not used in this study. As a result, the 10 ka climate experiment does not include the Laurentide Ice Sheet. Although the Laurentide Ice Sheet played an integral role in shaping the climate of North America during the Last Glacial Maximum (LGM) and the subsequent deglaciation, it was significantly reduced by the start of the Holocene. Also, neglecting the influence of the Laurentide Ice Sheet enables me to focus exclusively on the role of orbital variations on climate change.

For my experiments I used the CLM-CN model, which includes nitrogen limiting effects on the carbon cycle. The biogeochemistry model is based on the Biome-BGC model and includes a fully prognostic carbon and nitrogen cycle (Thorton et al., 2007). The CLM-CN accounts for carbon and nitrogen stocks and fluxes in vegetation, litter, and soil organic matter, while retaining the approximations for water and energy in the vegetation, snow, and soil columns in CLM (Kloster et al., 2010).

The National Center for Atmospheric Research (NCAR) provides initial conditions for select model component setups that have already been spunup and equilibrated (i.e. model simulations that have been run for thousands of model years). These spunup initial conditions from NCAR are referred to as startup files. For these experiments, I obtained the startup files for the "E1850CN" component set from NCAR's data repository. Using these startup files I ran a single 100-year equilibrium run of CESM to ensure that the model was equilibrated for our purposes. To check for equilibrium I looked for any significant trends in the two-meter air temperatures and the global soil carbon stock.

In CLM, Alaska's boreal forests are modeled as needleleaf evergreen forests, which are characterized by White Spruce. In addition to White Spruce, CESM includes a small percentage of bare ground in boreal forests in its land-surface model (Bonan et al., 2002). The PFT determination for modern vegetation is initially done using the Moderate Resolution Imaging Spectroradiometer (MODIS) to differentiate fractional bare ground and forested land cover (Hansen et al., 2003). Advanced Very High Resolution Radiometer (AVHRR) is then applied to differentiate the forested land into broadleaf/needleleaf and evergreen/deciduous forest types (DeFries et al., 2000). Further differentiation of plant types into tropical, temperate, and boreal is done using a series of physiological and climatological rules (Nemani and Running, 1996). The modern vegetation datasets available from NCAR are used in both experiments in this study.

Wetlands are an important ecosystem in Alaska and play an integral role in dictating where peatlands are most likely to accumulate. NCAR includes wetland extent in the initial forcing data; however, these wetlands are not true wetlands as they exist in nature. Currently, wetlands in CLM 4.0 are modeled as open columns of water lacking soil and a representative vegetation plant functional type (PFT; Oleson et al., 2010). For these experiments I used the change in the fractional area where the water table is at the surface as an indicator for the relative change in wetland area. Although this version of CESM included the fully prognostic carbon-nitrogen biogeochemical model, my preliminary results showed a significant low bias of soil carbon in the Arctic. This low soil carbon in the boreal region is due to excessively dry soils in the permafrost zone and the lack of an anoxia function in CLM that regulates the decomposition of soil carbon under saturated conditions (D. Lawrence, personal communication, 8/10/11).

*2b. Terrestrial Ecosystem Model*

To circumvent the aforementioned issue with Arctic soil carbon in CESM, output from the CESM experiments was used to force the Terrestrial Ecosystem Model (TEM). TEM is a biogeochemical model of carbon, nitrogen, and water cycling for terrestrial ecosystems. This version of TEM (TEM-Hydro; Felzer et al., 2009) has multiple vegetation carbon and nitrogen pools for each structural component (leaves, sapwood, heartwood, roots, and labile), an organic carbon and nitrogen soil pool, and an inorganic nitrogen soil pool. Carbon is transferred between the atmosphere and vegetation via gross primary productivity (GPP) and autotrophic respiration. Carbon and nitrogen enter the organic carbon and nitrogen pools by litterfall. Heterotrophic respiration returns carbon to the atmosphere from the soils. In TEM-Hydro, nitrogen is only transferred internally between the vegetation and soil, via litterfall, net nitrogen mineralization, and plant nitrogen uptake, and is not input from the atmosphere or leached from the soils. The parameters that determine the fluxes are based on calibration to sites with long-term ecological measurements. For Alaska, these sites include Bonanza Creek for boreal forest and Toolik Lake for dry and moist tundra. The Bonanza Creek boreal forest site consists of 80% Black Spruce, 10% White Spruce, and 10% mix of upland hardwoods (Van Cleve et al., 1983). TEM experiments for this study were run at the same 1.9° x 2.5° resolution as CESM and are forced by climate input from the CESM experiments. Input parameters for TEM include; precipitation, two-meter air temperature, vapor pressure, wind velocity, solar surface insolation, and the average daily temperature range. Other fields that are required by TEM, but remain constant throughout all of the experiments, include soil type, elevation, and PFT. I ran TEM in equilibrium mode, which assumes that the carbon and nitrogen fluxes are in balance and that the annual carbon and nitrogen inputs are equal to the annual losses, resulting in a Net Ecosystem Productivity (NEP) of zero.

Both CESM and TEM have similar vegetation PFTs; one key difference is that this version of TEM does not include a wetland PFT. However, TEM does include a moist tundra PFT. The moist tundra PFT in TEM includes moist tundra, wet tundra, and some high grasses that are found in Alaska's wetlands (Joint Federal-State Land Use

Planning Commission for Alaska, 1973). However, this PFT has not been developed to account for particular carbon and nitrogen dynamics of wetlands.

Initial TEM experiments resulted in extremely low vegetation and soil carbon in Alaska. Comparing observed temperatures at Bonanza Creek (Mitchell et al., 2003; CRU TS 2.0) to simulated temperatures by CESM at the same location revealed that CESM temperatures were approximately 10°C too low in the elevated $CO_2$ experiment. Gridded temperature data (Mitchell et al., 2003; CRU TS 2.0) for Alaska was upscaled from the initial 0.5° x 0.5° resolution to the same 1.9° x 2.5° resolution as the CESM experiments. Temperatures from the elevated atmospheric $CO_2$ were compared to the upscaled observed temperatures in order to calculate temperature biases across all of Alaska. The calculated biases were added to the temperature values that were initially used to force TEM. Rerunning the TEM experiments with the bias-corrected data yielded vegetation carbon and soil carbon values consistent with those at Bonanza Creek

### *2c. Experiment Design*

I conducted two experiments, one with elevated $CO_2$, and another with 10 ka orbital parameters. The experiment with elevated $CO_2$ used the default orbital parameters from NCAR's present-day model experiments (1990 A.D.) and atmospheric $CO_2$ concentration was set to 368.9 ppmv. For the 10 ka orbital experiment I set the orbital parameters to those of the HTM (Berger, 1978) and set the atmospheric $CO_2$ concentration at the preindustrial level (280 ppmv). Although the atmospheric $CO_2$ levels inferred from ice cores are slightly lower than 280 ppmv at 10 ka, setting atmospheric $CO_2$ levels equal to preindustrial values allowed me to analyze the impact of atmospheric $CO_2$ directly attributed to industrialization. Each of these experiments were run for 100 years and initialized using the output from my initial 100-year equilibrium run.

I used a 30-year period from the end of each of the model runs (i.e. years 70 – 99) for the final analysis. This procedure allowed CESM an additional 70 years to equilibrate and acclimate to the elevated atmospheric $CO_2$ concentrations and 10 ka orbital parameters.

*2d. Statistical Analysis*

I used the student's t-test to determine the significance of many of the results in this study. The unpaired two-sample student's t-test is used to compare two separate sets of independent and identically distributed samples. In this case, the two samples that were compared were the results from my CESM experiments. The 95$^{th}$ confidence interval was used in this study as the significance threshold. Any of the differences that failed at this threshold were noted in the results section, but were not deemed to be significant results.

## 3. Results

*3a. CESM Results*

The effect of 10 ka orbital forcing on solar insolation at the top of the atmosphere (TOA) is more radiation during the boreal summer and less insolation during the boreal fall and winter than present (Figure 1). At 10 ka, the Earth received 40 – 50 W/m$^2$ more insolation during summer (June, July, and August) than present JJA insolation at the TOA. Additionally, there is a slightly less significant reduction in insolation during the fall and winter months for the latitudes that encompass Alaska. Although the amount of insolation at 10 ka has significant seasonal differences from present, the total amount of insolation received annually is virtually identical. Furthermore, higher latitudes have more of a seasonality change in insolation than lower latitudes.

The significant differences in insolation seasonality between the two experiments have a large role in dictating the observed temperature differences. DJF temperatures (Figure 2) in Alaska exhibit a strong north-south temperature gradient, primarily governed by the amount of insolation received. Results indicate that DJF temperatures in the elevated $CO_2$ experiment are warmer throughout all of Alaska. The largest warming is located in the northern portions of Alaska along the Brooks Range extending into eastern Alaska. Although the temperatures in these regions are approximately 1 – 2 °C warmer than the 10 ka orbital experiment, statistical analysis show that these temperature differences are not significant.

Average JJA temperatures (Figure 3) in the two experiments have less of a pronounced north – south temperature gradient and exhibit a larger influence of topography on temperature. The regional temperature minima coincide with the highest topography in Alaska, namely in the regions encompassing the Wrangell, Chugach, Alaska, and Brooks Mountain Ranges. Results indicate that the experiment with elevated $CO_2$ has lower JJA temperatures than the 10 ka orbital experiment. The elevated $CO_2$ experiment is approximately 1 – 2 °C cooler than the 10 ka orbital experiment in northern Alaska along the Brooks Range. These temperature differences in northern Alaska are statistically significant.

Both DJF and JJA temperatures are combined to determine the temperature seasonality of a region; I used the difference between the average JJA temperature and the average DJF temperature as a measure of seasonality (Figure 4). Both experiments have a strong north – south gradient in temperature seasonality, with the largest temperature seasonality located along the Brooks Mountain Range. The elevated $CO_2$ experiment (Figure 4b) exhibits less temperature seasonality throughout the entirety of Alaska, with the largest decreases in northern Alaska. There is approximately 3 °C less temperature seasonality in northern Alaska along the Brooks Range in the elevated $CO_2$ experiment compared to the 10 ka orbital experiment. These differences in temperature seasonality throughout northern and portions of eastern Alaska are statistically significant.

Permafrost thawing is another potential source of soil moisture in Alaska (Figure 5). In both experiments the majority of permafrost is limited to the northern portions of Alaska along the Brooks Range and in the southeastern portion of Alaska encompassing the Wrangell and Alaska Mountain Ranges. Results indicate that there is more permafrost located in northern Alaska in the elevated $CO_2$ experiment compared to the 10 ka orbital experiment. Additionally, there is a slight reduction in the amount of permafrost in the southeastern parts of Alaska in the elevated $CO_2$ experiment. Only the increases in permafrost along the Brooks Range in northern Alaska in the elevated $CO_2$ experiment are statistically significant.

The average snowpack depth (Figure 6) throughout Alaska in the 10 ka orbital experiment is consistently deeper than the average snowpack depth in the elevated $CO_2$ experiment during the late-fall through early-spring months. The snowpack depths in the two experiments are similar during the typical melt season for Alaska's snowpack. Both experiments show a peak depth in the snowpack in April prior to rapid melting during the months of April, May, and June. A majority of Alaska is snow-free by the end of June. Initiation of snowpack accumulation for the following winter begins in September in both of the experiments.

Differences in snowpack depth between the two experiments will result in differences in the average amount of snowmelt experienced throughout Alaska (Figure 7). Both experiments show the onset of spring snowmelt occurring in late March and early April, with peak snowmelt occurring in May. In late May and early June the amount of snowmelt begins to be limited by the depth of the snowpack. By late June most of Alaska is snow-free, rendering snowmelt contributions to surface runoff negligible throughout the majority of Alaska. Although there appears to be no difference in snowmelt timing and duration between the two experiments, there is a substantial difference in the amount of snowmelt in Alaska. Results indicate during the month of May, portions of Alaska in the 10 ka orbital experiment receive approximately 1 mm/day more snowmelt than it receives in the elevated $CO_2$ experiment.

Average daily runoff (Figure 8) for Alaska indicates that the timing and the magnitude of peak seasonal runoff for Alaska is essentially the same for both experiments. During the month of May, the elevated $CO_2$ experiment receives approximately 0.5 mm/day of runoff less than the 10 ka orbital experiment. This maximum in the difference of runoff coincides with the maximum difference in the average snowmelt throughout Alaska.

Runoff from spring snowmelt coupled with topography play a crucial role in dictating the location and expanse of wetlands in Alaska (Figure 9). The CESM simulated the majority of wetlands in Alaska are located along the southern reaches of Alaska, particularly in the southwestern part of Alaska where the terrain is much less mountainous. Results indicate that there is a greater wetland expanse in the 10 ka orbital experiment than in the elevated $CO_2$ experiment, although these results are not statistically significant.

Both experiments have the same general trend for JJA precipitation (Figure 10). The JJA precipitation maximum in both experiments is located in the southeastern portions of Alaska near the Wrangell Mountains. Although the experiments have the same general distribution of precipitation, the majority of Alaska receives less precipitation in the elevated $CO_2$ experiment than in the 10 ka orbital experiment. The largest reduction in JJA precipitation is located in the interior of Alaska in the area of the Yukon-Tanana Uplands. All of the differences in precipitation throughout Alaska are statistically significant.

Evapotranspiration in Alaska is primarily limited to the southwestern portions of Alaska (Figure 11). Both experiments show very little evapotranspiration at higher altitudes in the Brooks, Chugach, and Wrangell Mountain Ranges. Although the elevated $CO_2$ experiment shows less evapotranspiration than the 10 ka orbital experiment, none of these differences are statistically significant.

Volumetric soil moisture is similar in both experiments (Figure 12). The volumetric soil moisture maximum is located in the extreme southeastern portion of Alaska, with the coastal portions of Alaska having the largest values of volumetric soil moisture. Results indicate that the northern portions of Alaska as well as the extreme southern coastline have more volumetric soil moisture in the elevated $CO_2$ experiment than in the 10 ka orbital experiment, while having less volumetric soil moisture in the interior of Alaska. These differences are not statistically significant.

The regions of Alaska that have a fire season in CESM are limited to the southwestern and extreme northeastern portions of Alaska (Figure 13). Results indicate that the fire season in southwestern Alaska is approximately two weeks longer in the elevated $CO_2$ experiment compared to the 10 ka orbital experiment. Additionally, the forests in the extreme northeastern reaches of Alaska have a fire season that is 2 – 6 days longer with elevated atmospheric $CO_2$ concentrations. Although this doesn't translate directly into more fires annually, it does increase the risk of fires and the subsequent release of more $CO_2$ to the atmosphere.

*3b. TEM Results*

Calculated NPP (Table 1) values from the TEM experiments show that all three of the major biomes in Alaska are more productive in the elevated $CO_2$ experiment. Dry tundra NPP in the elevated $CO_2$ experiment is more than double the dry tundra NPP in the 10 ka orbital experiment. Calculated NPP values for the moist tundra biome with elevated $CO_2$ is 18% greater than the NPP value in the 10 ka orbital experiment, while the boreal forest biome experiences an increase of approximately 15% compared to the 10 ka orbital experiment.

Heterotrophic respiration ($R_h$; Table 2) is also greater in all three of the biomes in the elevated $CO_2$ experiment compared to the 10 ka orbital experiment. $R_h$ in dry tundra is approximately double that in the 10 ka orbital experiment. Calculated $R_h$ values in both the moist tundra biome with elevated $CO_2$ and boreal forest biomes with elevated $CO_2$ are approximately 11% greater than the values in the 10 ka orbital experiment.

The amount of organic carbon in the vegetation and soil is much greater in the elevated $CO_2$ experiment than the 10 ka orbital experiment for each biome (Tables 3, 4). Vegetation carbon is more than doubled in dry tundra, 26% larger in moist tundra, and 31% larger in boreal forest. The greater amount of vegetation carbon results in more litterfall and therefore more carbon in the soil. Soil carbon is 88% larger in dry tundra, 14% larger in moist tundra, and 12% larger in the boreal forest.

## 4. Discussion

*4a. Permafrost*

Permafrost in Alaska plays an integral role in sequestering organic carbon from the atmosphere. Permafrost regions located throughout Alaska, in particular along Alaska's North Slope, contain high percentages of carbon that are withheld from the region's carbon cycle (Bockheim, 2006). The majority of the permafrost in both CESM model experiments is located at higher latitudes, primarily along Alaska's North Slope, as would be expected (Yershoc, 1998). Additionally, permafrost in these modeling experiments is located in southeastern Alaska at higher altitudes as well. As an indicator for permafrost, I used the presence of soil ice during the summer months. This index assumes that the bulk melting of soil ice in Alaska would have concluded by the end of August, and any remaining soil ice remains frozen perennially.

Summer temperature is a major factor in controlling permafrost extent. Increases in summer temperatures will result in a net loss in the permafrost extent (Shuur et al., 2008). The loss of permafrost in Alaska will mobilize previously sequestered carbon through methanogenesis (Anisimov, 2007). One study of ongoing permafrost thawing in Russia suggests that by mid-21$^{st}$ century the annual flux of methane to the atmosphere will increase by 25%, or an additional 0.04 ppmv of methane (Anisimov, 2007). Increased temperatures in the aforementioned study lead to an increase in the thickness of the active-layer, where the permafrost is affected by seasonal freeze/thaw cycles and the bulk of methanogenesis occurs. Summer temperatures in both of these experiments are higher than preindustrial JJA temperatures. As a result, the active-layer in both is enhanced, potentially yielding more methanogenesis. However, JJA temperatures in the

10 ka orbital experiment are higher than in the elevated $CO_2$ experiment, which results in less permafrost and potentially greater releases of methane from thawing permafrost at 10 ka.

My hypothesis was that warming due to elevated atmospheric $CO_2$ would result in less permafrost than at 10 ka. These modeling results suggest the opposite, at least with present-day $CO_2$ concentrations (368.9 ppmv). Although my initial hypothesis regarding Alaskan permafrost was incorrect, atmospheric $CO_2$ concentrations will continue to rise. The latest IPCC report (2007) suggests that $CO_2$ concentrations will be far in excess of 500 ppmv by the year 2100, ranging from 550 ppm for the SRES B1 scenario to 820 ppm for the SRES A2 scenario (Meehl et al., 2007). Higher $CO_2$ concentrations in the near future will result in even higher summer temperatures than those in this study. If summer temperatures as a result of elevated $CO_2$ eclipse summer temperatures resulting from 10 ka orbital parameters, it will likely result in more permafrost thawing and the release of more methane in the future. To test this hypothesis, another experiment could be designed using an estimated $CO_2$ level for 2100.

### *4b. Peatlands*

It has been previously shown that Alaskan peatlands experienced a period of rapid accumulation at 10 ka (Yu et al., 2009; Jones and Yu, 2010). Peatlands accumulate in regions where anaerobic conditions limit decomposition; as a result productivity exceeds decomposition leading to the accumulation of partially decomposed organic carbon (Frolking et al., 2001; Charman, 2002; Yu et al., 2009; Jones and Yu, 2010). Although northern peatlands are the largest natural source of methane (Crill et al., 1988), they have served as a net sink of carbon from the atmosphere over the past millennia. It is estimated that northern peatlands extract 0.02 – 0.03 kg $CO_2$-C $m^{-2}$ $yr^{-1}$ from the atmosphere (Gorham, 1995). It is estimated that over the past 5,000 – 10,000 years northern peatlands have accumulated 200 – 450 Pg C (Gorham, 1991). One study suggests that elevated atmospheric $CO_2$ concentrations threaten to reduce the expanse of wetlands, limiting their ability to preserve organic carbon and turn the peatlands into a potential carbon source (Turetsky et al., 2002).

Climatological results from CESM indicate a warmer and wetter climate in both experiments, but more so with 10 ka orbital parameters. The deeper snowpack and warmer summer temperatures result in more snowmelt and runoff than as a result of elevated atmospheric $CO_2$ concentrations. Additionally, CESM shows more precipitation with 10 ka orbital parameters. Both of these modeling results suggest more wetland area with 10 ka orbital parameters than as a result of elevated atmospheric $CO_2$ concentrations. CESM results confirm the climatological portion of my hypothesis regarding Alaskan peatlands. Warmer and wetter conditions in the 10 ka orbital experiment are more conducive to substantial peat accumulation and preservation of organic carbon, despite the more favorable conditions for methane emissions via methanogenesis.

Although CESM suggests that the climatological conditions with 10 ka orbital parameters are more favorable for the accumulation of peat, the TEM experiments indicate the opposite. The regions in Alaska that were classified as moist tundra (most analogous biome to wetlands) have more soil carbon at the end of the experiment with elevated atmospheric $CO_2$ concentrations than due to 10 ka orbital conditions. These results indicate that moist tundra is more susceptible to organic carbon accumulation with elevated atmospheric $CO_2$ concentrations than with 10 ka orbital conditions. Moist tundra is modeled as a terrestrial ecosystem in TEM-hydro rather than an aquatic ecosystem like true wetlands. It is possible that using a wetlands model that has more accurate carbon dynamics would increase carbon accumulation with warmer and wetter conditions during 10 ka, due to reduced microbial decomposition.

*4c. Boreal Forest*

Boreal forests are extremely large stores of organic carbon, both in the soil and vegetation (Gower et al., 1997). Boreal forest productivity is predominately limited by temperature. Higher temperatures have resulted in more productive forests and increased carbon uptake from the atmosphere (Keeling et al., 1996). Both experiments simulate warm periods in the Earth's history and should exhibit enhanced productivity as a result. CESM results indicate that summer temperatures are warmer with 10 ka orbital parameters than with elevated atmospheric $CO_2$ concentrations. This outcome refutes my initial hypothesis that summer temperatures would be warmer with elevated $CO_2$ concentrations, leading to greater boreal forest productivity compared to 10 ka orbital parameters.

Additionally, studies have suggested that warming from elevated $CO_2$ concentrations have recently caused Alaska's boreal forests to show signs of drought stress (Barber et al., 2000). CESM shows no significant changes in soil moisture and evapotranspiration, so drought stress should not have any influence on the productivity of either experiment. CESM also suggests a longer fire season throughout southeastern

Alaska, which confirms the part of my hypothesis regarding the lengthening of the fire season in Alaska due to elevated atmospheric $CO_2$ concentrations, although fire is not explicitly modeled in these experiments.

The forests that were present in Alaska at 10 ka were not similar to the boreal forests that are present today. Non-analogue Poplar forests dominated the Alaskan landscape at 10 ka, but transitioned to the modern Spruce-dominated boreal forests around 9 ka (Yu et al., 2009). Both vegetation maps used in these experiments were the modern vegetation that is present in Alaska today. This choice was made to provide a consistent set of boundary conditions between the experiments. The TEM experiments reveal that the boreal forests are more productive with elevated atmospheric $CO_2$ concentrations despite the cooler summer temperatures (relative to 10 ka). The higher productivity is reflected in higher NPP values and increased vegetation carbon.

Boreal forests included in this study are unique ecosystems compared to other types of forests (i.e. tropical and temperate). Boreal forests typically have a lower optimal temperature for photosynthesis (Smith et al., 2001) and a higher base rate of respiration (Hickler et al., 2008). Despite these differences, several studies have linked enhanced $CO_2$ fertilization to increased NPP values throughout the major forest types (Melillo et al., 1993; Cramer et al., 2001). It is likely that the increase in NPP in the elevated $CO_2$ experiment is the result of enhanced $CO_2$ fertilization.

Although these results support my hypothesis, the root cause of the increased productivity in these experiments is likely the result of enhanced $CO_2$ fertilization and not elevated temperatures as I suggested. However, it is important to keep in mind that $CO_2$ concentrations in the Earth's atmosphere will continue to rise well into the 21$^{st}$ century.

This increase will result in temperatures that are 2°C – 4°C warmer than those present in the elevated $CO_2$ experiment (IPCC, 2007), and subsequently more productive boreal forests.

## 5. Conclusions

The Earth's climate has experienced significant change over the past century (Keeling et al., 1979; IPCC, 2007). Ecosystems located at higher latitudes have been subjected to the brunt of these changes (Lachenbruch and Marshall, 1986; Buckland et al., 2008; Johannessen et al., 1999; Comiso, 2002), especially resulting from warming. Many of these ecosystems play vital roles in the boreal carbon cycle. Permafrost and peatlands sequester carbon, while boreal forests extract $CO_2$ from the Earth's atmosphere. There is significant concern that increasing global temperatures will result in thawing of permafrost, drying of wetlands, and changes to the fire regimes, all of which will result in substantial releases of methane and $CO_2$ (Field and Raupach, 2004).

Increases in both temperature and $CO_2$ are causing profound changes to Alaskan ecosystems. It is difficult to separate the impacts of warming from the effects of elevated $CO_2$ concentrations. Fortunately, the Earth has experience numerous warm periods in the past where elevated temperatures were not accompanied by higher $CO_2$ concentrations (e.g. the Holocene Thermal Maximum; HTM).

Using the HTM as an analogue for future warming provides a valuable glimpse into the climatological and biogeochemical characteristics of many of Alaska's sensitive ecosystems. This study shows that changes to Alaska's carbon cycle have offsetting implications as a result of elevated $CO_2$ concentrations. Using CESM and TEM-hydro to directly compare present anthropogenic climate change to the HTM it was shown that: 1) warmer temperatures in both experiments will reduce permafrost extent (Shuur et al., 2008); however, more permafrost is present with elevated atmospheric $CO_2$ concentrations than with 10 ka orbital parameters, resulting in the release of less methane from methanogenesis compared to 10 ka, 2) reduced wetland expanse from warming due to elevated atmospheric $CO_2$ levels, as opposed to more wetlands from 10 ka warming, results in the potential for more methane emissions from Alaskan peatlands in the present compared to 10 ka, and 3) both experiments are designed to model relatively warm periods in the Earth's history, which increases NPP and carbon uptake in Alaska's boreal forests (Keeling et al., 1996); however, boreal forests are more productive with elevated atmospheric $CO_2$ concentrations despite slightly cooler summer temperatures compared to 10 ka orbital parameters. This result is likely caused by enhanced $CO_2$ fertilization in Alaska's boreal forest regions, yielding a larger carbon sink compared to 10 ka. Additionally, CESM indicates a longer fire season with elevated $CO_2$ concentrations. This trend has the potential to release larger amounts of carbon to the atmosphere and offset any increase in carbon uptake via enhanced $CO_2$ fertilization (Zhuang et al., 2006).

Although many of the aforementioned changes to Alaska's carbon cycle have positive implications, one should use caution when analyzing these results. There are a number of changes that can be applied to future experiments to increase the accuracy of these modeling results. Crucial changes to CESM are needed to improve hydrologic and decomposition processes at higher latitudes, addressing temperatures biases, as well as including a true wetlands model in CESM or TEM-hydro.

One final difference that should be taken into consideration is the conceptual design of these experiments themselves. As society continues to develop, atmospheric $CO_2$ concentrations will continue to increase, elevating observed temperatures further. The atmospheric $CO_2$ concentrations present in the elevated $CO_2$ experiment were set to values that have already been exceeded. It is uncertain how high atmospheric $CO_2$

concentrations will go. The latest IPCC report (2007) shows values will exceed 550 ppmv by the year 2100, which is much higher than the 368.9 ppmv used in this study. It will therefore be imperative to monitor the response of these sensitive ecosystems in the future. Any further increases in temperature will thaw more permafrost and dry more wetlands than in these experiments, creating even larger sources of methane, exacerbating anthropogenic carbon emissions.

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## 7. Figures

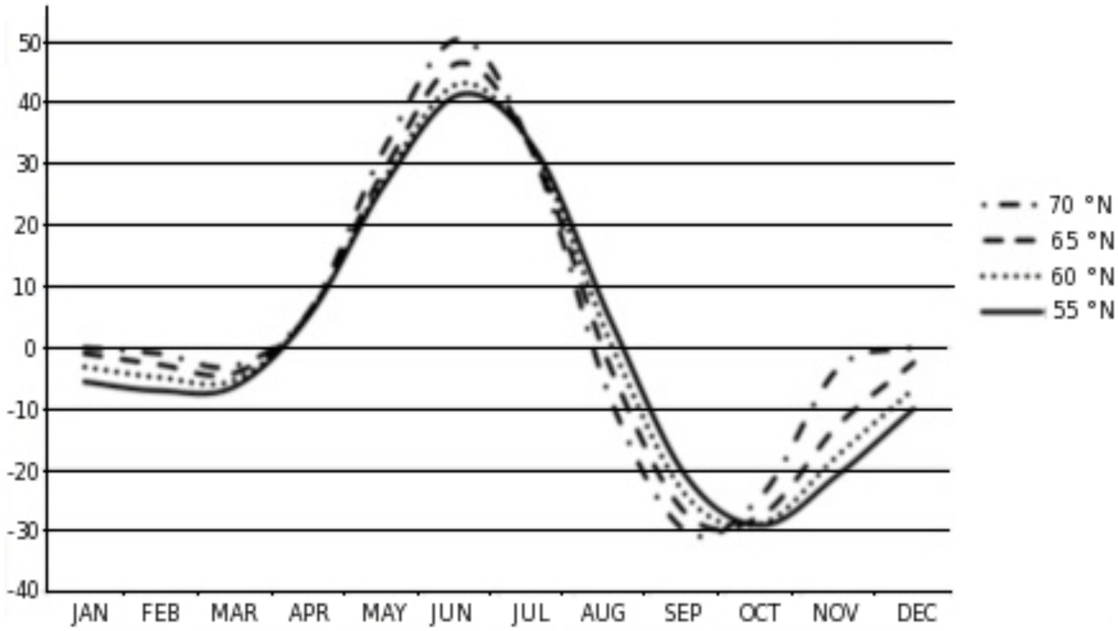


**Figure 1. Difference in insolation at the top of the atmosphere in CESM experiments (10 ka Orbital – Elevated $CO_2$) ($W/m^2$).** During JJA higher latitudes received more insolation at 10 ka compared to present. During DJF at 10 ka higher latitudes receives less insolation than present.

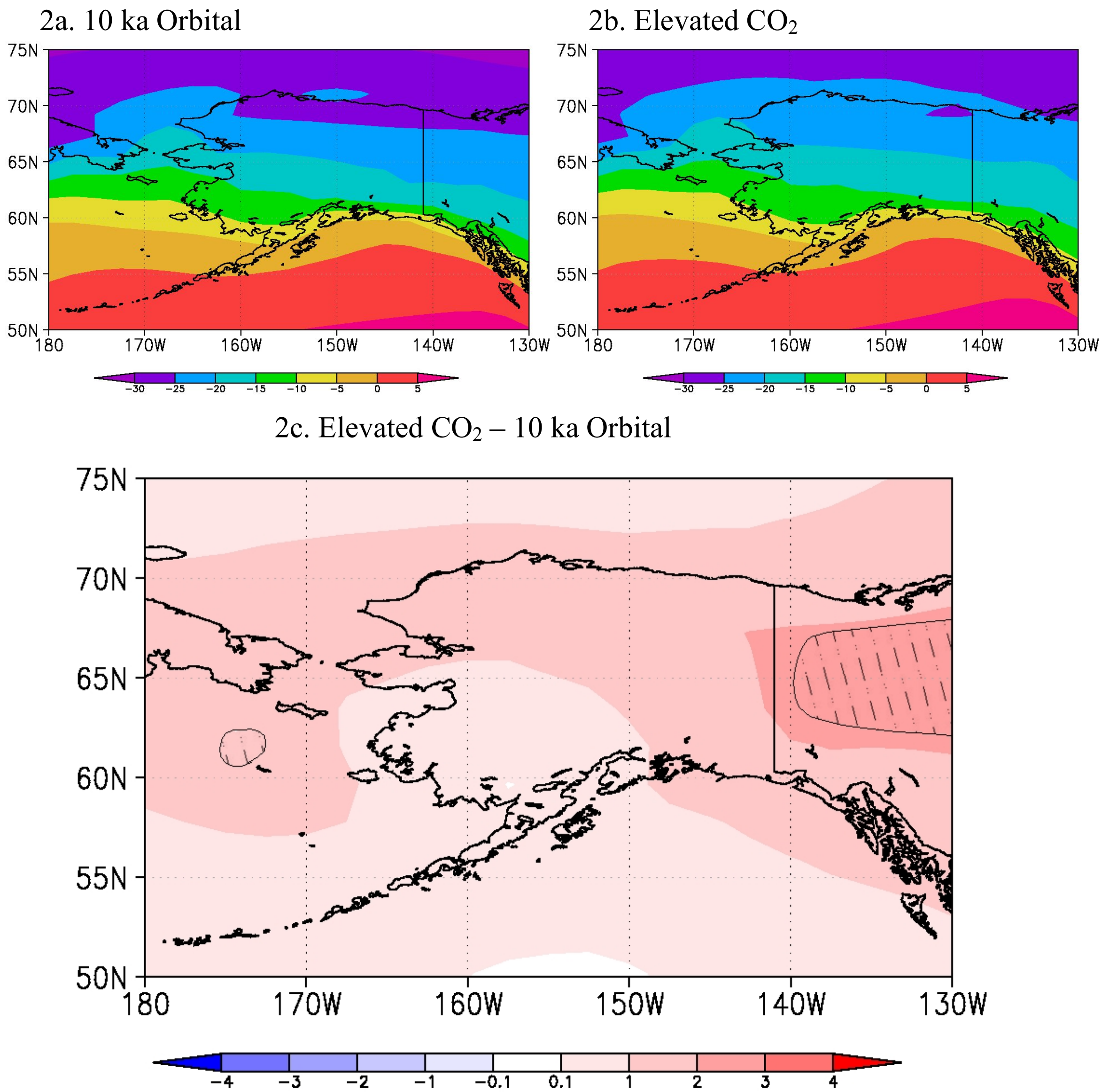


**Figure 2. CESM DJF Temperatures (°C).** (2a) DJF temperatures from the 10 ka Orbital experiment. (2b) DJF temperatures from the Elevated $CO_2$ experiment. (2c) Absolute difference in DJF temperatures (Elevated $CO_2$ experiment – 10 ka Orbital experiment); regions highlighted with the dot-dash pattern indicate statistically significant differences in temperature between the two experiments. None of the statistically significant differences in DJF temperatures were located in Alaska.

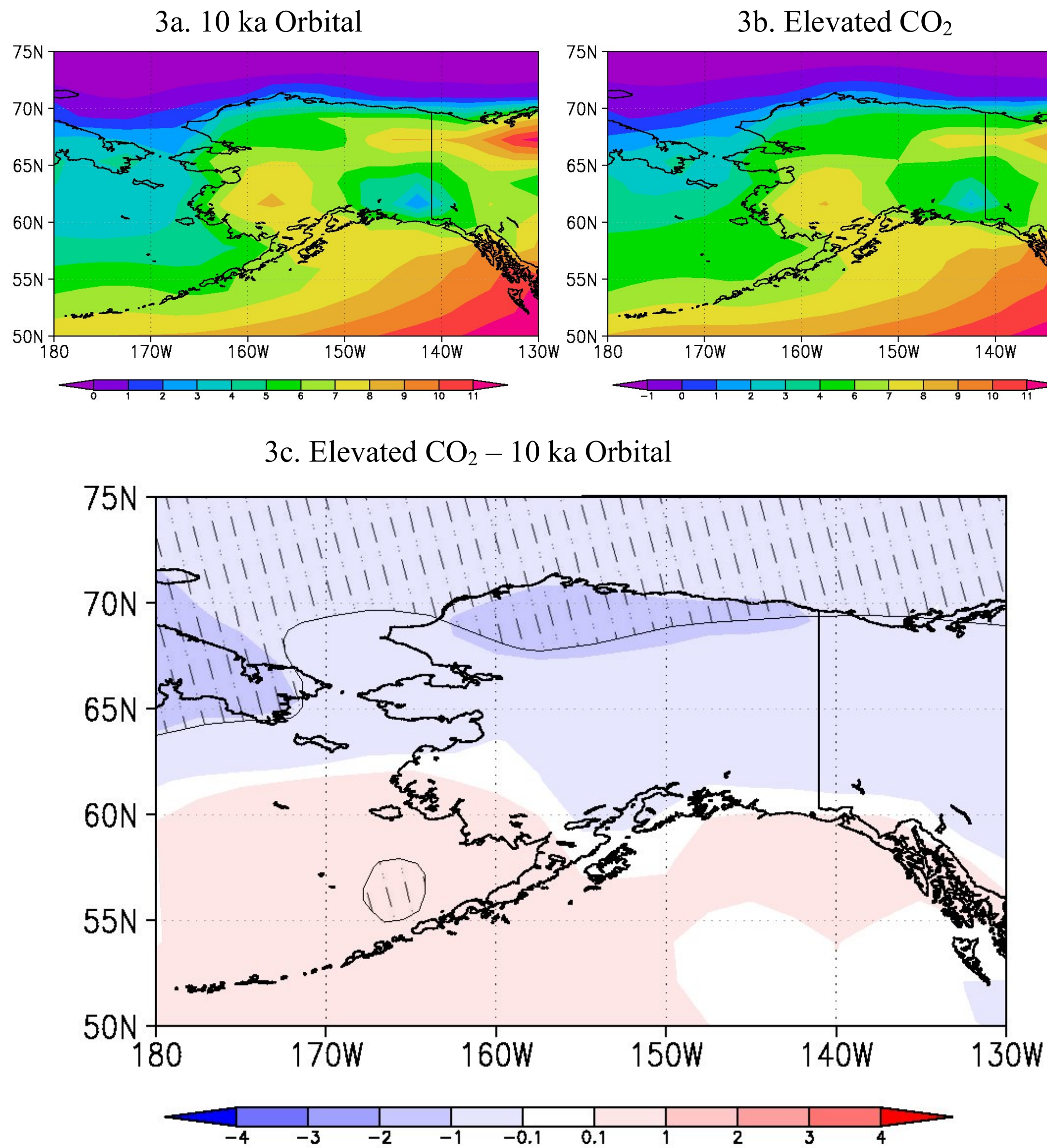


**Figure 3. CESM JJA Temperatures (°C).** (3a) JJA temperatures from the 10 ka Orbital experiment. (3b) JJA Temperatures from the Elevated $CO_2$ experiment. (3c) Absolute difference in JJA temperatures (Elevated $CO_2$ experiment – 10 ka Orbital experiment); regions highlighted with the dot-dash pattern in northern Alaska along the Brooks Range indicate statistically significant differences in temperature between the two experiments.

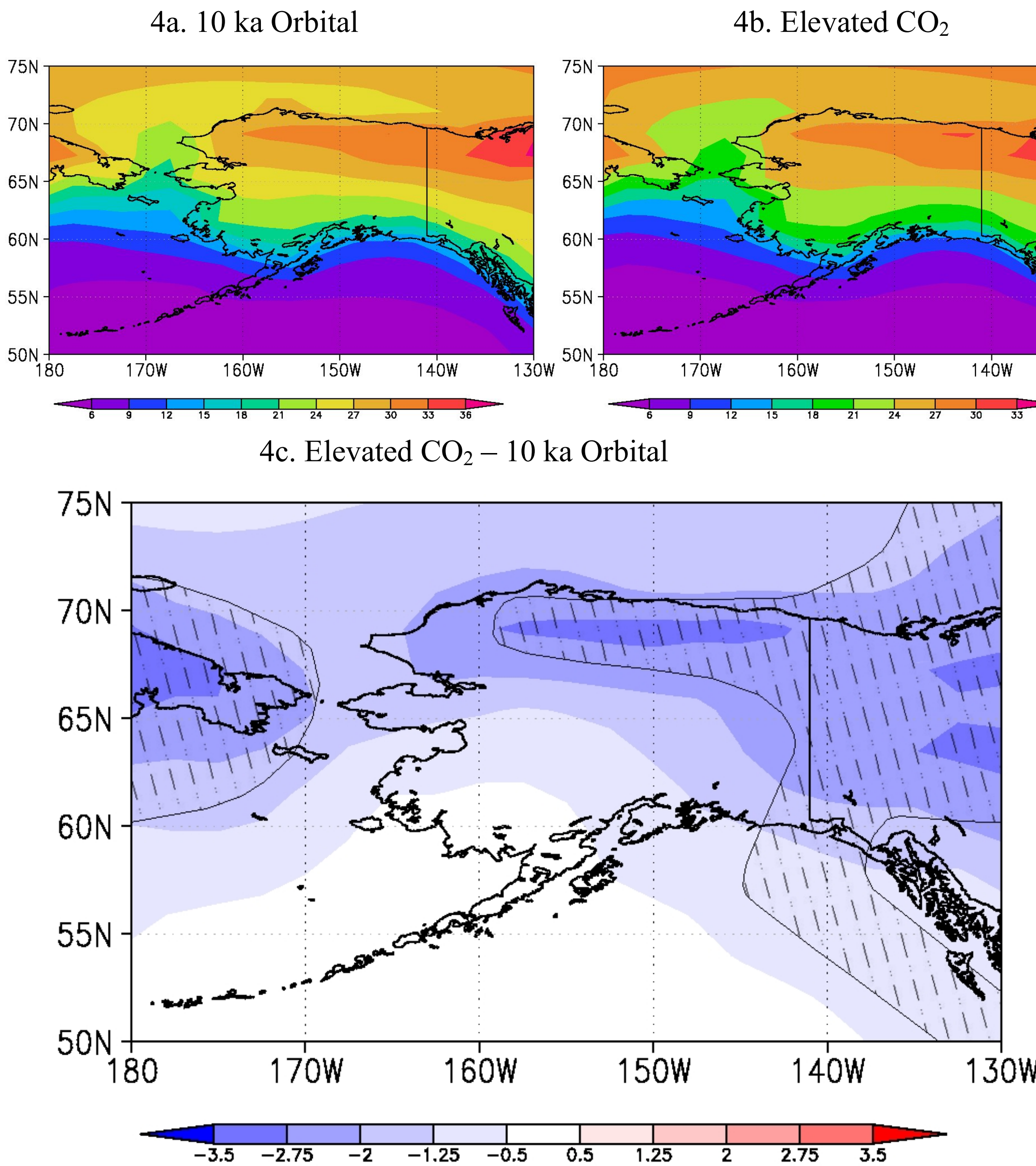


**Figure 4. CESM Temperature Seasonality (°C).** (4a) Temperature seasonality from the 10 ka Orbital experiment. (4b) Temperature seasonality from the Elevated $CO_2$ experiment. (4c) Absolute difference in temperature seasonality (Elevated $CO_2$ experiment – 10 ka Orbital experiment); regions highlighted with the dot-dash pattern in northern Alaska along the Brooks Range and in western Alaska indicate statistically significant differences in temperature seasonality between the two experiments.

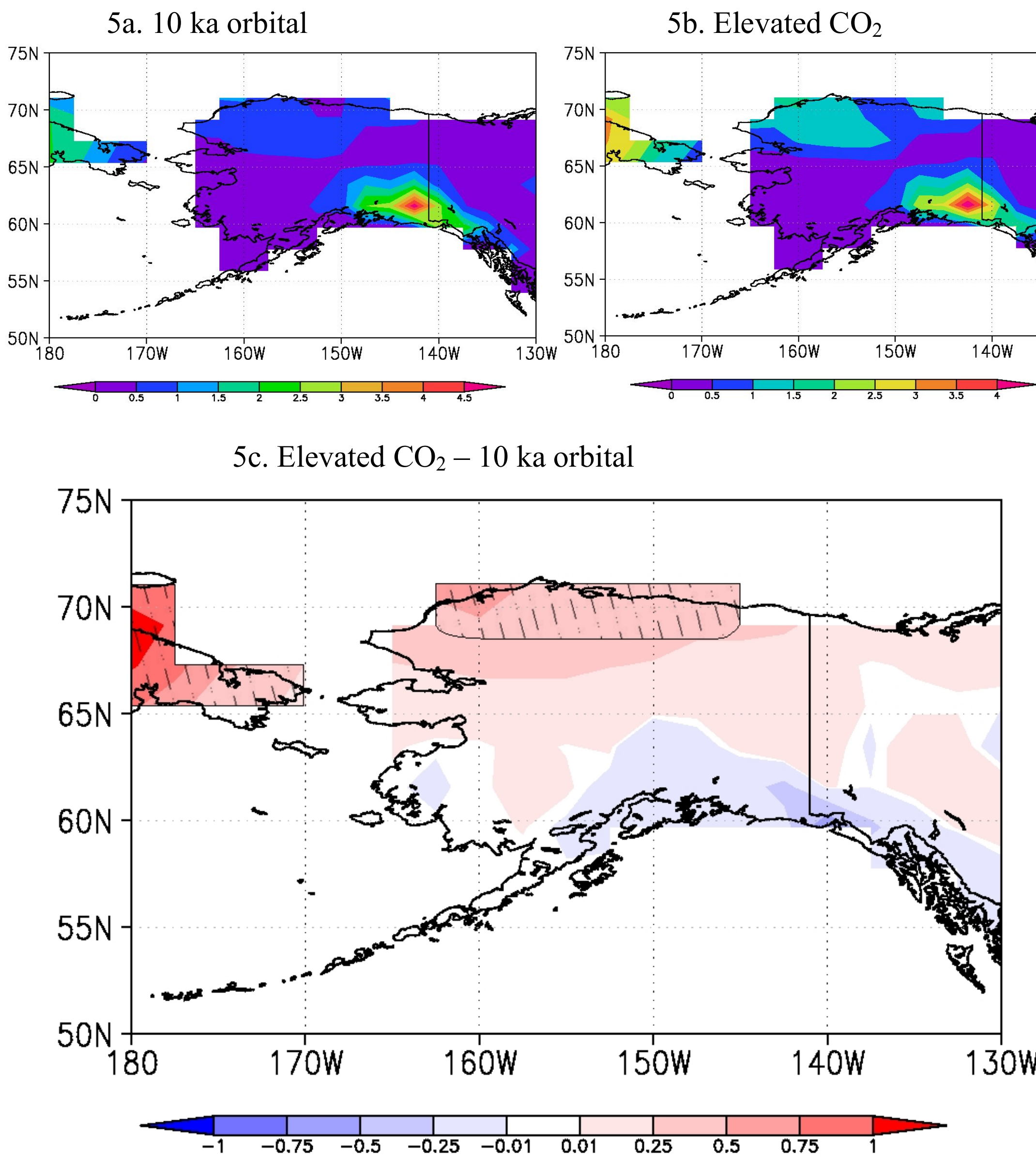


**Figure 5. CESM Permafrost (kg/m$^2$ frozen water in soil column).** (5a) Permafrost in the 10 ka Orbital experiment. (5b) Permafrost in the Elevated $CO_2$ experiment. (5c) Absolute difference in permafrost density (Elevated $CO_2$ experiment – 10 ka Orbital experiment); regions highlighted with the dot-dash pattern in northern Alaska along the Brooks Range indicate statistically significant differences between the two experiments.

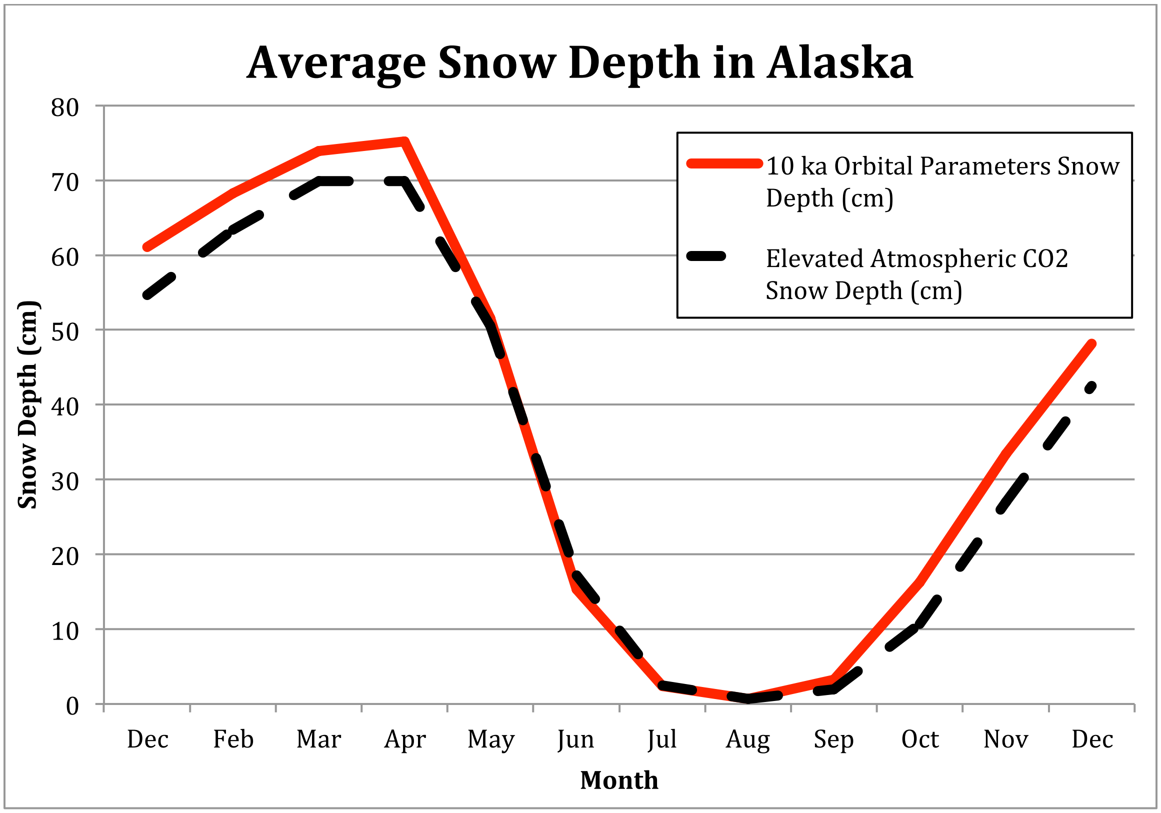


**Figure 6. CESM Snow Depth Averaged Throughout Alaska.** The red line indicates the average snow depth throughout Alaska in the 10 ka Orbital experiment. The black dashed line indicates the average snow depth throughout Alaska in the Elevated $CO_2$ experiment. Both experiments have the same timing of the peak and tough, with snowpack growth initiating in September and initial snowpack reduction beginning in April. By late June most regions in Alaska are snow-free. The 10 ka Orbital experiment indicates a 5 – 6 cm increase in snowpack depth compared to the Elevated $CO_2$ experiment.

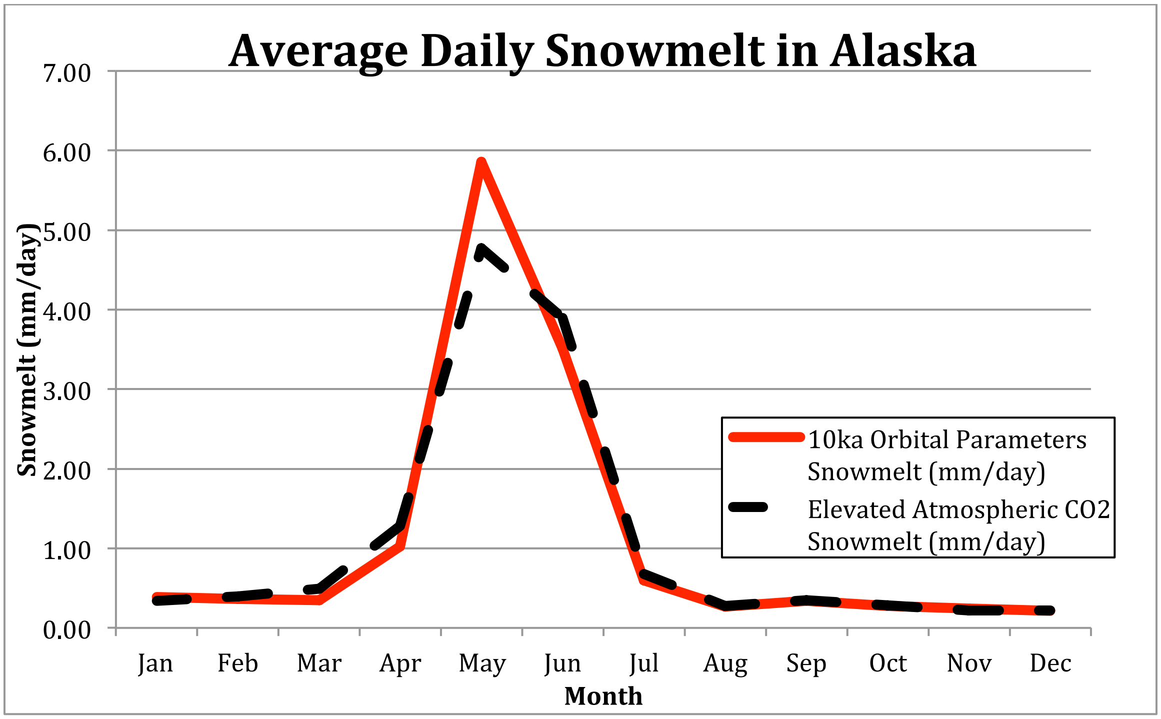


**Figure 7. Daily Snowmelt Averaged Throughout Alaska.** The red line indicates the average daily snowmelt throughout Alaska in the 10 ka Orbital experiment. The black dashed line indicates the average daily snowmelt throughout Alaska in the Elevated $CO_2$ experiment. Both experiments show initial snowmelt occurring in April, with a peak in snowmelt occurring in May as the snowpack throughout Alaska has reduced substantially from its initial depth. By July, snowmelt throughout much of Alaska has ceased, as more of the Alaskan landscape has become snow-free. The 10 ka Orbital experiment indicates a 1 mm/day increase in snowmelt compared to the Elevated $CO_2$ experiment.

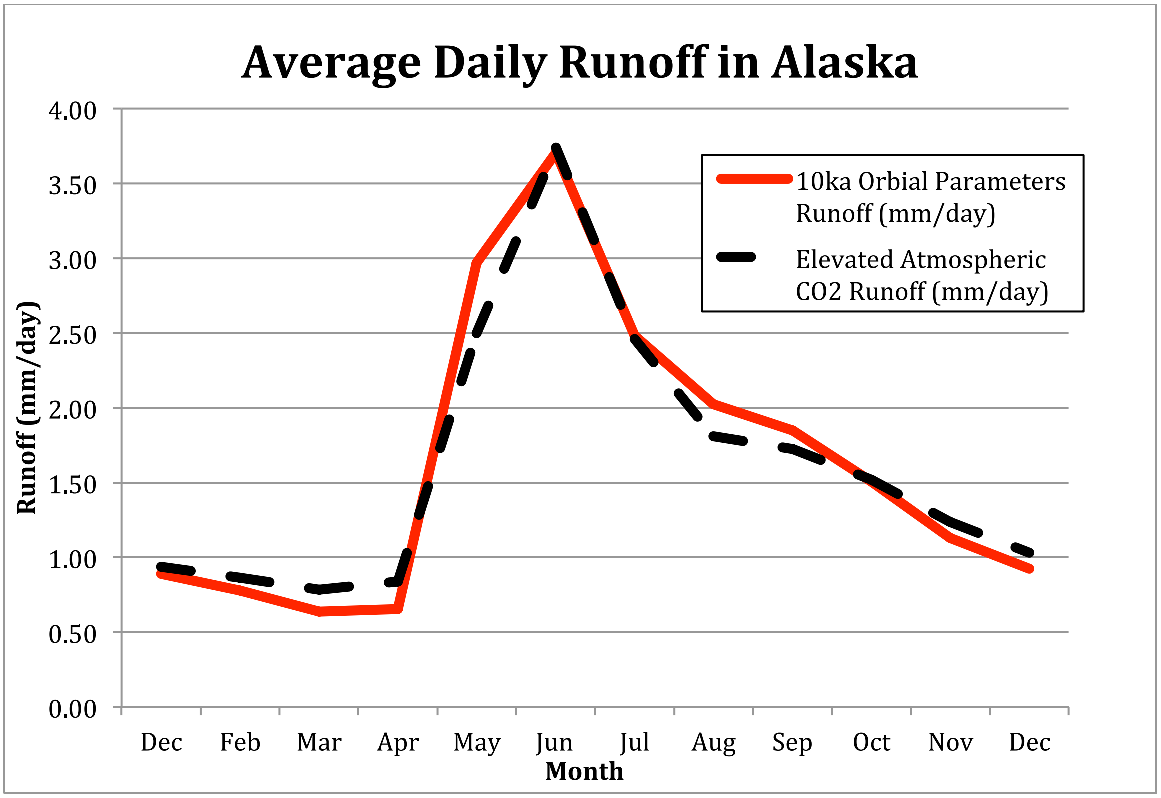


**Figure 8. Daily Surface Runoff Averaged Throughout Alaska.** The red line indicates the average daily runoff from my 10k Orbital experiment. The black dashed line indicates the average daily runoff from my Elevated $CO_2$ experiment. Both curves follow the same general trend with a sharp increase in surface runoff in April, a peak in runoff in July, and a rapid decline thereafter.

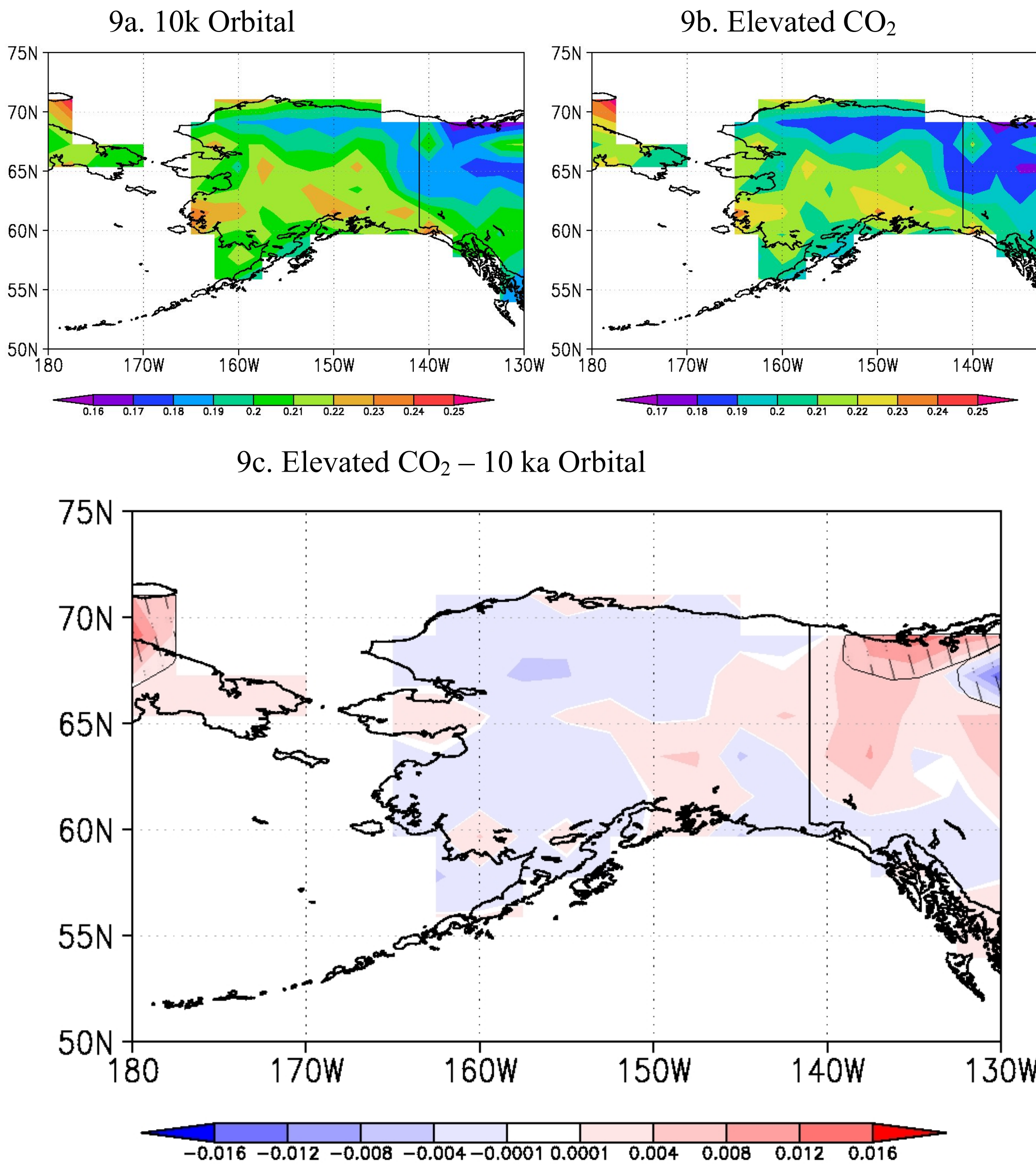


**Figure 9. CESM Wetland Expanse (percent area).** (9a) wetland expanse in the 10 ka Orbital experiment. (9b) Wetland expanse in the Elevated $CO_2$ experiment. (9c) Absolute difference in wetland expanse (Elevated $CO_2$ experiment – 10 ka Orbital experiment); regions highlighted with the dot-dash pattern are statistically significant. None of the significant differences in wetland expanse between the two experiments are located in Alaska.

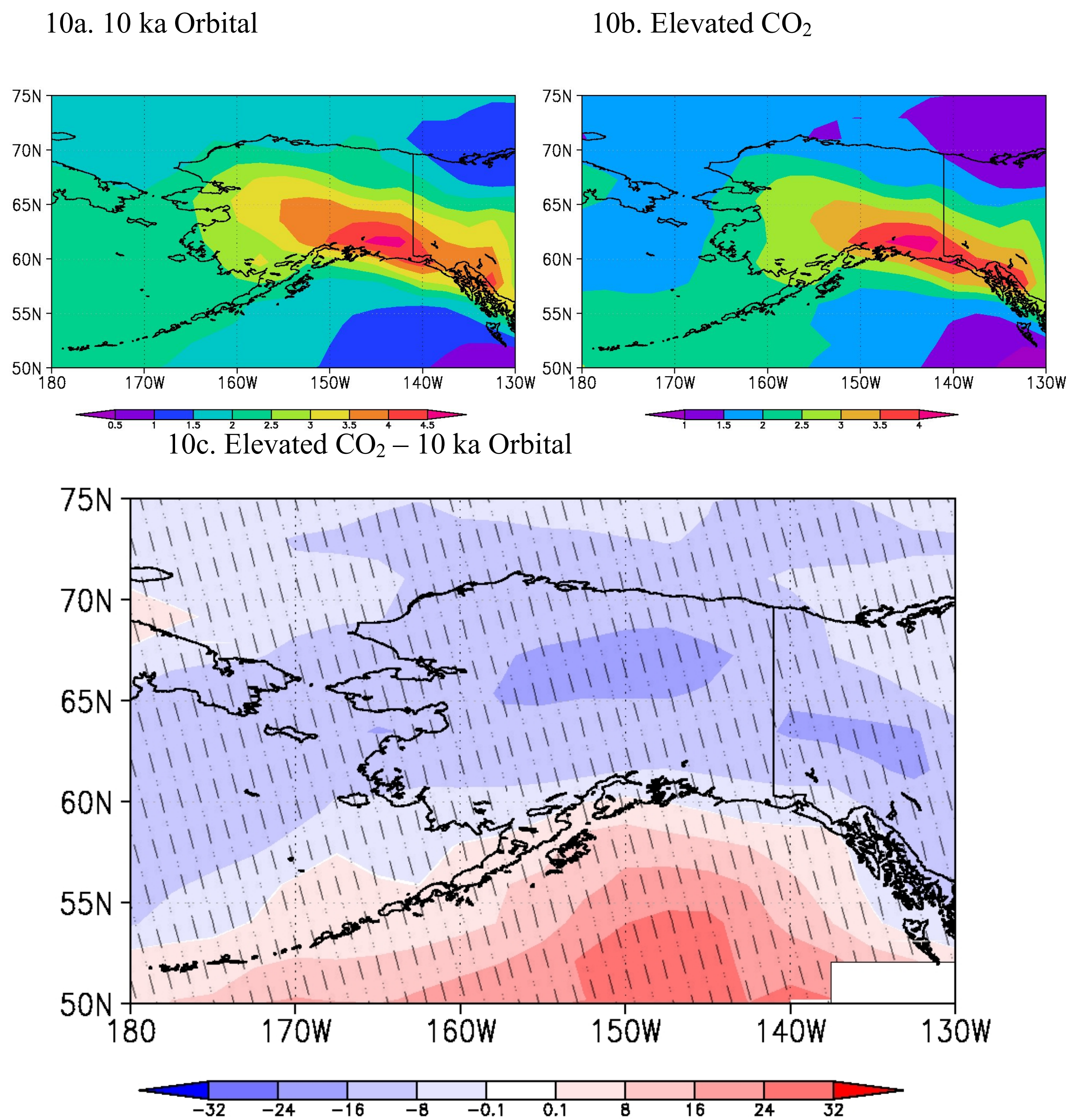


**Figure 10. CESM JJA Precipitation (mm / day).** (10a) JJA precipitation in the 10 ka Orbital experiment. (10b) JJA Precipitation in the Elevated $CO_2$ experiment. (10c) Percent difference in JJA precipitation (Elevated $CO_2$ experiment – 10 ka Orbital experiment); regions highlighted with the dot-dash pattern encompassing the entirety of Alaska are statistically significant differences in JJA precipitation.

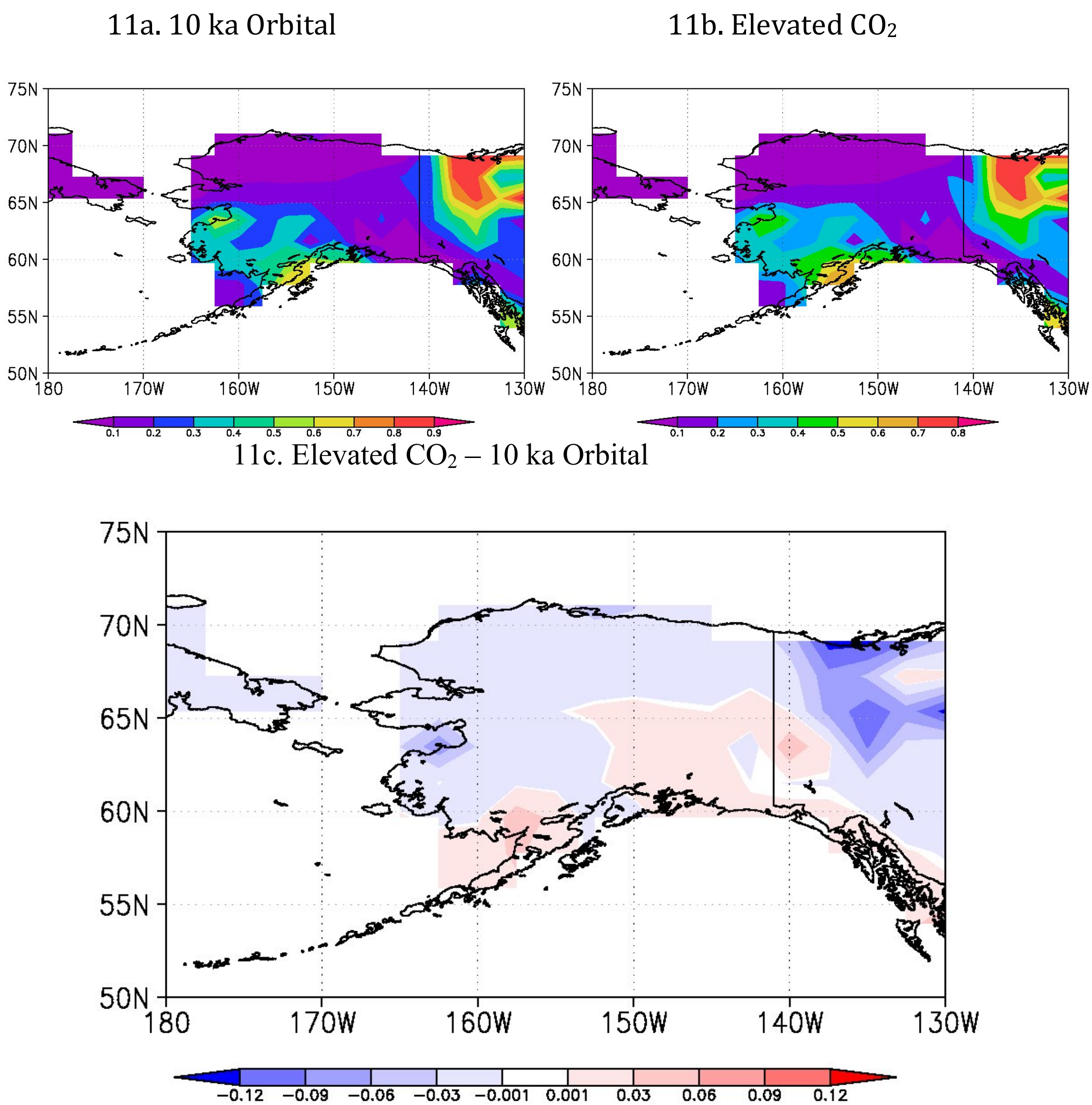


**Figure 11. CESM Evapotranspiration (mm / day).** (11a) Evapotranspiration in the 10 ka Orbital experiment. (11b) Evapotranspiration in the Elevated $CO_2$ experiment. (11c) Absolute difference in evapotranspiration (Elevated $CO_2$ experiment – 10 ka Orbital experiment). None of the differences in Alaska are statistically significant.

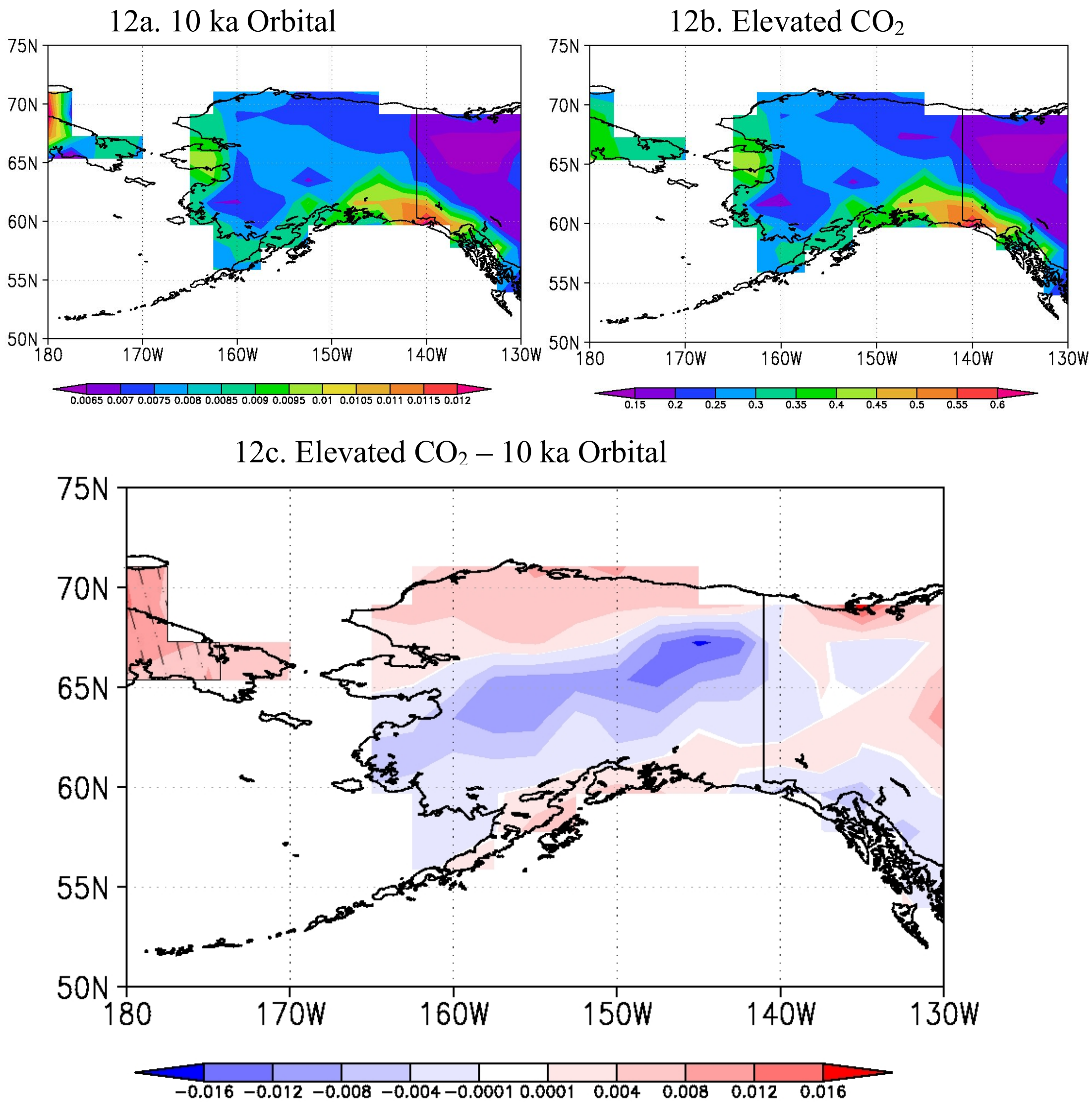


**Figure 12. CESM Volumetric Soil Moisture (mm$^3$ / mm$^3$).** (12a) Volumetric soil moisture in the 10 ka Orbital experiment. (12b) Volumetric soil moisture in the Elevated $CO_2$ experiment. (12c) Absolute difference in volumetric soil moisture (Elevated $CO_2$ experiment – 10 ka Orbital experiment); none of the differences in volumetric soil moisture in Alaska are statistically significant.

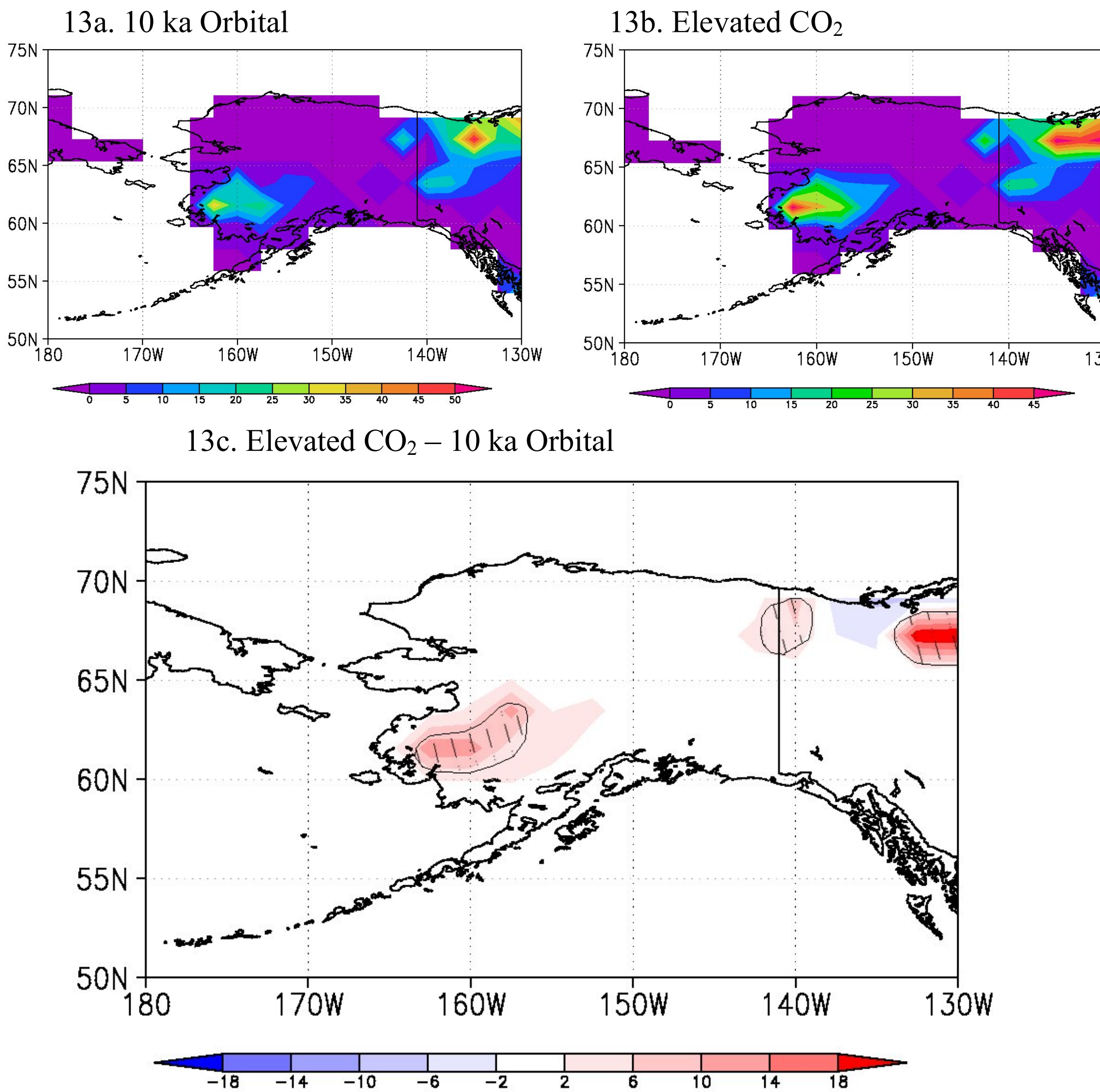


**Figure 13. CESM Fire Season Length (days).** (13a) Fire season length in the 10 ka Orbital experiment. (13b) Fire season length in the Elevated $CO_2$ experiment. (13c) Absolute difference in fire season length (Elevated $CO_2$ experiment – 10 ka Orbital experiment); regions highlighted with the dot-dash pattern in southwestern and northeastern portions of Alaska are statistically significant.

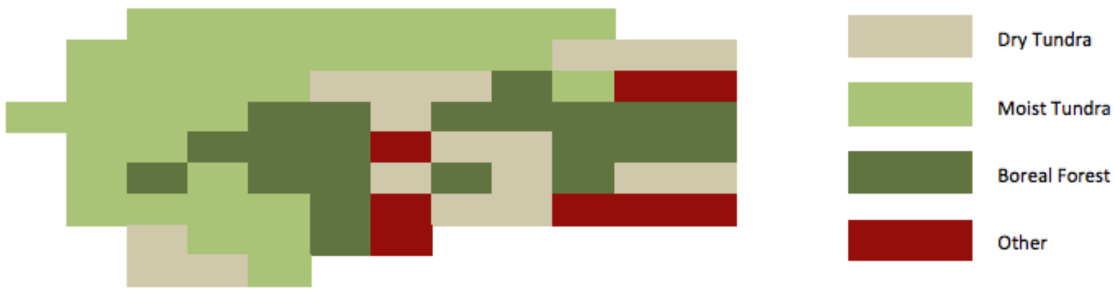


**Figure 14. Alaska Biome Map for TEM Experiments.** The three major biomes in Alaska include: 1) dry tundra (tan), 2) moist tundra (light green), and 3) boreal forests (dark green).

**8. Tables**

**Table 1. Calculated JJA NPP values from TEM experiments (g C $m^{-2}$ $month^{-1}$).**

| | Dry Tundra | Moist Tundra | Boreal Forest |
|---|---|---|---|
| 10 k orbital Experiment | 2.11 | 23.83 | 25.16 |
| Elevated CO2 Experiment | 5.22 | 29.02 | 29.49 |

**Table 2. Calculated JJA Rh values from TEM experiments (g C $m^{-2}$ $month^{-1}$).**

| | Dry Tundra | Moist Tundra | Boreal Forest |
|---|---|---|---|
| 10k Orbital Experiment | 2.04 | 18.97 | 24.56 |
| Elevated CO2 Experiment | 4.23 | 21.43 | 27.82 |

**Table 3. Vegetation carbon stock from TEM experiments (g C $m^{-2}$).**

| | Dry Tundra | Moist Tundra | Boreal Forest |
|---|---|---|---|
| 10k Orbital Experiment | 34.08 | 394.54 | 2965.69 |
| Elevated $CO_2$ Experiment | 80.69 | 497.13 | 3875.29 |

**Table 4. Soil carbon stock from TEM experiments (g C $m^{-2}$).**

| | Dry Tundra | Moist Tundra | Boreal Forest |
|---|---|---|---|
| 10k Orbital Experiment | 730.01 | 7974.76 | 6992.11 |
| Elevated CO2 Experiment | 1373.96 | 9116.26 | 7815.89 |

## 9. Curriculum Vitae

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